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EFFECT OF AN ELECTRICAL FIELD ON A LIQUID STREAM

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[Figures in parenthesis refer to the appended bibliography.]

I. INTRODUCTION

In 1897 Rayleigh noticed for the first time that the breaking down of a stream from a water fountain diminishes under the influence of electric-static forces (1). However, he did not investigate this phenomenon in sufficient detail, and offered no satisfactory theory to explain it. Later investigations likewise led to no substantial success in understanding its nature (2). However, they did establish the fact that the stabilizing effect of the electrical field on a stream of liquid, noticed by Rayleigh, takes place only in the case of weak fields, whereas strong electrical fields produce an opposite effect, namely increased breaking down of the stream.

The experiments described below confirmed these results and defined them more precisely. Furthermore, they ascertained a number of essential details which, to the best of our knowledge, had not been noted previously, and which permit one to give a sufficiently full -- although only qualitative and not quantitative -- explanation of Rayleigh's effect.

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II. EXPERIMENTS WITH A WATER FOUNTAIN

Our experiments were made on a strictly vertical thin stream of water (upwards), in an electrical field parallel to it, i. e., vertical. The latter was created with the aid of two horizontal tin disks 135 mm in diameter, in the center of which circular openings 40 mm in diameter had been cut out, and which were connected to the opposite poles by a small electrostatic machine. We also tried to investigate the effect on the stream of a transverse horizontal field. However, slight asymmetry in the arrangement of the stream in relation to the electrodes resulted in its abruptly expressed attraction toward one of them (the nearer one); therefore we limited ourselves to the investigation of the effect of a longitudinal vertical field, which would not complicate the phenomena being studied with extraneous circumstances.

Our arrangement was extremely simple. It consisted of a glass vessel with a side aperture, to permit the liquid to flow out, from which the water was conducted by means of a rubber hose to a nipple ending in an aperture ($d = 0.8$ mm). The electrodes were joined to the opposite poles of a small electrostatic machine driven by hand rotation. The minimum voltage which could be obtained with slow rotation of the handle (according to measurements with an electrostatic voltmeter) was 2500 V. The maximum voltage at the poles of the machine reached $3 \cdot 10^4$ V. The distance between the outlet of the vessel and the aperture of the nipple was 45 cm. The height of the stream fluctuated from 20 to 25 cm depending on the diameter of the rubber hose and the pressure.

The lower electrode was placed below the beginning of the breakup of the stream into drops; the upper electrode, considerably higher.

Upon switching on the field at a voltage of 125 V/cm a peculiar periodical "squatting" of the stream was observed. At the end of the stream a small drop is formed, the dimensions of which gradually increase, and then the drop falls together with the stream. Finally the drop flows down along the core of the stream, after which the latter rises to its original level and the phenomenon is repeated. It does not depend on the polarity of voltage impressed on the electrodes.

The phenomenon in question is evidently explained by the stabilization of the stream under the influence of the electrical field; that is, by a diminution of spattering as a result of which a gradually growing drop develops on the peak of the stream.

Upon increasing the voltage of the field above $E = 125$ V/cm there occurs a stabilization of the stream and increased spattering. Along with this, the height at which the breakup of the stream begins, drops abruptly (to 8 cm, i. e., five-fold). The dimensions of the drops are much smaller than in the absence of the field. In this case the beginning of the breakup of the stream drops from 10 to 3 cm, counting from the end of the aperture of the nipple. No dependence on the polarity of the impressed voltage was observed. It is natural to suppose that the spattering was dependent on the electrical forces of repulsion between similarly charged drops.

For determining the polarity of their charge, an arrangement was set up consisting of a half electrometer connected with a cylindrical vessel into which individual drops of water fell. As a result it was established that the polarity of discharge of the drops coincided with the polarity of charge of the lower disk.

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III. EXPERIMENTS WITH NONCONDUCTING LIQUID AND WITH A DILUTE SOLUTION OF POTASSIUM HYDROXIDE

In order to ascertain the influence of an electrical field on the spattering of a nonconducting liquid, experiments were made with transformer oil. The great viscosity, of the oil in comparison with water, impeded the free flowing of the stream; therefore, it was necessary to create some pressure in the vessel with the aid of an air pump. The experiments demonstrated that the phenomenon of "squatting", observed in the stream of water in a weak electrical field, was completely absent in the transformer oil. The spattering of the stream of oil under the effect of a strong electrical field was observed in a very weak form. Thus, the spattering of liquids depends essentially on their electroconductivity.

In addition to water and transformer oil, a weak aqueous solution of potassium hydroxide was also used. The phenomenon of "squatting" of the stream in this case was obtained just as with pure water; but the spattering was much more abrupt than was the case with the stream of water.

IV. MECHANISM OF STABILIZATION OF THE STREAM IN WEAK ELECTRICAL FIELDS

The experiments described demonstrate that the stabilization of the stream of liquid under the influence of a weak electrical field is not connected with the surface characteristics of the liquid (with its surface tension or its electrocapillary effects), but is dependent exclusively on its electroconductivity. This means that the cause of this stabilization should be sought in the phenomena of electrical induction produced by the field in the conducting stream. Evidently the induction must amount to the electrification of the upper and lower ends of the stream; also, these charges must be opposite in polarity to the charges of the corresponding electrodes.

In the absence of an electrical field, the breakup of a thin stream is preceded, as is known, by the formation of a number of constrictions. The gradual increase of these constrictions leads to the disintegration of the upper end of the stream into separate drops.

In the presence of a relatively weak electrical field, the situation is complicated by electrical forces of attraction, which develop between adjacent links of a chain of drops forming before its disintegration, and which impede disintegration. These forces of attraction are dependent on the longitudinal polarization of the separated drops; the force of attraction sustained by one of them (e. g., the outer one) from the preceding one is equal to $\frac{6p^2}{r^4}$ (p is the electrical moment of the drop, equal to the product of the volume of the external electric field E_0 , in which the stream is located, and the cube of the radius of drop a ; r is the distance between centers of adjacent drops). Assuming approximately that $r = 2a$, we obtain:

$$\frac{6p^2}{r^4} \approx \frac{3}{4} \frac{a^6 E_0^2}{a^4} \approx a^2 E_0^2$$

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With $a = 2\text{mm}$ and $E = 1000\text{ V/cm} = 30\text{ cse}$, the force under consideration is about 1 dyne. In spite of the fact that it is weak nevertheless has great importance for the stabilization of the stream, impeding the fracture of the latter into separate drops. Therefore a large drop must grow on the upper end of the stream which, pressing on the stream with its weight, gradually causes it to drop. By this, as already mentioned above, the phenomenon of the pulsation of the stream in an electrical field is explained. The period of this pulsation τ may be calculated by comparing the weight of the "macrodrop" growing on the end of the stream during time τ with the hydrostatic pressure which maintains its level in the absence of the macrodrop at height h . If the forces of friction sustained by the macrodrop in flowing down along the upward-moving stream are not taken into consideration, then:

$$\tau = \sqrt{\frac{h}{2g}}$$

where g is the acceleration of the force of gravity. When $h = 10\text{ cm}$, this expression gives $\tau = 0.1\text{ second}$, whereas in the experiment τ has an order of one second. Such a discrepancy in all probability is explained by the effect of the forces of friction mentioned.

V. PULVERIZATION OF THE STREAM IN STRONG FIELDS

The pulverization effect exerted on the stream by a strong electrical field is explained by the circumstance that in the presence of a sufficiently large electrical charge, the upper drop loses its stability; that is, it acquires a tendency to divide into smaller ones. This loss of stability of the conducting liquid under the influence of a strong electrical field explains the spouting of a mercury electrode in strong electrical fields, as well as the division of heavy atomic nuclei possessing a large electrical charge. In the latter case the loss of stability is determined by the condition of equality of the square root of electrical energy to the doubled surface energy of the drop (4). Roughly speaking, this condition is equivalent to the equation of the surface pressure $\frac{\sigma}{r}$ (where σ is the surface tension) to the electrical pressure $\frac{E^2}{8\pi}$, that is, it amounts to the equation:

$$E = \sqrt{\frac{16\pi\sigma}{r}}$$

This equation is confirmed by a number of experimental data regarding deformations sustained by droplets of water, especially by those falling in strong electrical field (5).

Field E on the surface of the drop, crowning the stream of water, should not be identified with the average field E_0 , in which the stream is located. It is not difficult to show that with its height equivalent to h , $E = \frac{E_0 h}{a}$ (a is the radius of the drop) (5). Thus when $h = 10\text{ cm}$ and $a = 0.2\text{ cm}$, E is approximately 20 times greater than E_0 . Under such conditions E may reach a critical value determined by the preceding formula long before E_0 will reach that value. Thus, for example, assuming that $\sigma = 10^2$ and $r = 2 \cdot 10^{-1}\text{ cm}$, we obtain $E = 160\text{ cse} = 50,000\text{ V/cm}$, which corresponds to $E_0 = 2000\text{ V/cm}$. The latter value is close to that at which pulverization of the stream actually begins, according to our experiments. As has already been noted, the droplets into which it scatters have a charge of the same polarity as the lower electrode. The explanation cited agrees also with the fact that in the case of a nonconducting liquid (oil) the phenomenon of pulverization of the stream is scarcely observed; the same is true of the phenomenon of its stabilization in weak fields.

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